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Identification of a robust Lake Sturgeon (*Acipenser fulvescens* Rafinesque, 1917) population in Goulais Bay, Lake Superior

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Summary

Lake Sturgeon (*Acipenser fulvescens* Rafinesque, 1917) in Lake Superior are greatly depressed from their historic abundance, and few populations meet the rehabilitation goals identified by management agencies. A netting program targeting juvenile Lake Sturgeon (ages 3–15) was implemented from 2010 to 2012 in Goulais Bay, a shallow, productive bay in the south-eastern part of the lake, to determine abundance, distribution, population characteristics (size structure, condition, age structure, mortality and growth), and recruitment patterns. Five-hundred and thirty-one individuals were captured over the 3-year study, resulting in a mark-recapture estimate of 4977 (95% CIs 3295–7517) juveniles. Catch rates in this study were higher than in any other location in Lake Superior, with sturgeon being broadly distributed around the bay. Estimated annual survival rate ranged from 0.691 to 0.858, depending on the method used. The majority of fish captured were between 620 and 800 mm in total length and were between 4 and 10 years of age (range 1–29 years). Recruiting year-classes were apparent every year, with no apparent effects due to lampricide treatments (a suspected threat to age-0 Lake Sturgeon) in the Goulais River. Year-class strength was positively related to spring water levels. It is possible that this robust Goulais Bay population could help re-populate the south-eastern part of Lake Superior, which contains a number of large, productive embayment areas that formerly supported large Lake Sturgeon populations.

Introduction

Lake Sturgeon (*Acipenser fulvescens* Rafinesque, 1917) populations have remained below recovery targets throughout the Laurentian Great Lakes despite rehabilitation activities that have addressed many of the identified threats (Auer, 1999; Welsh et al., 2008; Chalupnicki et al., 2011). As a result, Lake Sturgeon are listed as a species of conservation concern in all political jurisdictions bordering the Great Lakes, with the exception of Wisconsin (Auer, 1999; COSEWIC, 2007). Lake Sturgeon are believed to be particularly vulnerable to anthropogenic activities due to specific life history characteristics, including slow growth and late maturation, intermittent spawning intervals, and habitat requirements such as specific temperature, flow velocities and substrate requirements for successful spawning (Peterson et al., 2007).

Lake Superior, the largest, deepest and coldest of the Laurentian Great Lakes, contains a number of poorly studied Lake Sturgeon populations that face unique challenges, even among the other Great Lakes (Auer, 2003). Anthropogenic impacts are relatively modest and Lake Superior is the most pristine of the Great Lakes, with <2% of its watershed impacted by urbanization or agriculture and over 90% of the catchment covered by forests or water features (LaMP, 2013). Despite its size, Lake Superior has a relatively simple ecosystem dominated by native species and has long been held as an example of an ecosystem that is minimally disturbed and slow to change, particularly in the face of immense changes in the other Great Lakes (e.g. Bronte et al., 2003; Mills et al., 2003; Dobiesz et al., 2005). Lake Sturgeon are restricted in Lake Superior to tributaries and a few, select inshore embayments as the vast majority of the lake is not suitable habitat due to cold temperatures, low productivity and extreme depths.

Lake Sturgeon were historically believed to spawn in 22 tributaries in Lake Superior, however eight of those populations are now thought to be extirpated due to exploitation, habitat loss, pollution, and migration barriers (Slade and Auer, 1997; Auer, 1999; Pratt, 2008). A rehabilitation plan was developed specifically for Lake Superior, which identified the development of lake-wide protocols for sampling the various life stages as key assessment needs (Auer, 2003). In response, a juvenile index netting protocol was developed and implemented in 2011 across the lake off the mouth of all historic spawning tributaries (Schloesser et al., 2014). In the rehabilitation plan, Auer (2003) identified four Lake Superior tributaries (the Sturgeon, Bad, St. Louis, and Nipigon rivers) where it was thought that the population might meet restoration targets.

The implementation of the lake-wide juvenile assessment allowed an opportunity to assess Lake Sturgeon populations throughout the lake. One sampling location, Goulais Bay, is a large (~80 km^2), relatively shallow (mean depth <20 m) embayment located in south-eastern Lake Superior, with the Goulais River identified as a tributary with an extant spawning population (Auer, 2003). South-eastern Lake Superior contains a number of large, shallow embayments (Whitefish Bay, Goulais Bay, Batchawana Bay) supporting diminished Lake Sturgeon populations that are genetically distinct from other Lake Superior populations (Welsh et al., 2008). Given the generally inhospitable habitat conditions for Lake Sturgeon in Lake Superior with the exception of very near-shore areas, the identification of a robust population in the south-eastern part of the lake that could produce sturgeon capable of using these shallow embayment areas might enhance lake-wide recovery efforts. We sampled the Lake Sturgeon population in Goulais Bay from 2010 to 2012 to determine the abundance, distribution, population characteristics (size structure, condition, age structure, mortality and growth) and recruitment patterns of the juveniles. We specifically focused on assessing the role of spring flow conditions in the Goulais River and lampricide control (a hypothesized mortality factor to age-0 Lake Sturgeon in Great Lakes tributaries) on the year-class strength of captured sturgeon.

Methods

Sampling

Lake Sturgeon were sampled following a juvenile index netting protocol designed to primarily target fish smaller than 1000 mm in total length and between age-3 and age-15, with some larger mesh included to ensure that the presence of adult fish was not missed (Schloesser et al., 2014). Two gangs of monofilament gill nets were combined to form a single continuous net 304.8 m long. Each gang contained three panels: 91.4 m of 11.4 cm stretched mesh, 30.5 m of 20.3 cm stretched mesh and 30.5 m of 25.4 cm stretched mesh. In 2010, 23 nets were set between 5 and 13 July. In 2011, 22 nets were set between 4 and 10 July, and in 2012, 27 nets were set between 3 and 9 July. Sampling locations in Goulais Bay were randomly chosen so that three distances from the spawning tributary were sampled (0–2 km, 2–5 km and 5–10 km; Fig. 1). Nets were set overnight for approximately 24 h in water between 3 m and 15 m in depth.

Captured fishes were recorded by panel number. Non-target fishes that were still alive were identified, weighed and released; dead non-target fishes were identified, weighed and set aside for disposal. Any Lake Sturgeon captured was immediately given a spaghetti tag applied on the dorsal surface immediately posterior to the dorsal fin, and placed in a live well filled with fresh lake water. The number on the tag and the mesh size were recorded immediately. Each fish was measured for total length (mm), fork length (mm), girth (mm, largest circumference posterior to pectoral fins), and weight (g). Captured sturgeon were checked for tags and signs that a tag might have been lost. An 11 mm full duplex passive integrated transponder (PIT) tag was inserted below the 3rd dorsal scute, and a 32 mm half-duplex PIT tag was inserted to the left of the ventral mid-line posterior to the pelvic fins. The small incision for the 32 mm PIT tag was closed with a small amount of VetbondTM. In addition, a 1 cm slice of the leading fin ray on the left pectoral fin was removed for age interpretation. Fish were then returned to the lake, and released once they could swim away on their own.

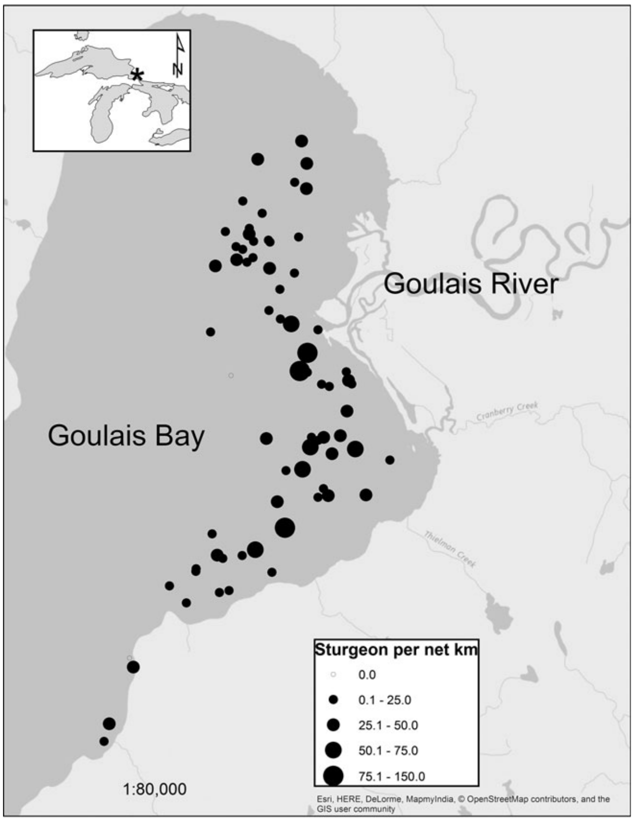

Fig. 1. Map of sampling locations, Goulais Bay, Lake Superior, with Lake Sturgeon (*A. fulvescens*) catch, represented by number of sturgeon captured per gill net km

Pectoral fin rays were dried for at least 4 weeks prior to sectioning. Each fin ray had two 300 μm sections cut from it using a Buehler IsoMet low-speed saw. Digital imaging software was used to amplify the fin ray section to estimate the number of annuli. Age was interpreted by two experienced biologists who independently assessed both fin ray sections and decided on the most likely age. Any ageing discrepancies were examined by a third person, and the majority age assigned. Fin-ray section photographs were also shared with other sturgeon age-interpreters from around the Lake Superior basin to provide further confidence in our age assessments.

Data analyses

The number of Lake Sturgeon captured per net set (CPUE) was calculated using the arithmetic mean. These means were then converted into the number of fish per km of net set. CPUEs from Goulais Bay in 2010–2012 were compared with the results of juvenile Lake Sturgeon assessments from other Lake Superior tributaries sampled in 2011 (Schloesser et al., 2014) to provide an assessment of the relative size of the Goulais Bay population in contrast with the other *A. fulvescens*-producing tributaries on Lake Superior. Juvenile recaptures (i.e. <100 cm) were used to estimate abundance, recapture probabilities and survival using the program MARK (White, 2011). Four models were evaluated, with the model having a single estimate of survival (ϕ) and daily varying return $(p(t))$ and probability of entering the population rate $(pent(t))$ probabilities providing the best model fit.

We also assessed mortality using catch curve analysis on pooled data from 2010 and 2011. The 2007 year-class was selected as the first fully recruited to the sampling gear (age-4); the last selected for the analysis was the year-class that had a minimum of Lake Sturgeon sampled (1994). Instantaneous total mortality was calculated as the slope of the catch-curve model relating the natural logarithm of the number of Lake Sturgeon in each year-class as a function of age. Total annual mortality was estimated as $1-e^{-slope}$. Captured Lake Sturgeon size and structure was qualitatively examined by inspection of frequency histograms of total length and age. Growth was examined by plotting the relationship between total length and age. Mortality, survival and the von Bertalanffy growth function were estimated using the FSA package (Ogle, 2012) in R (version 2.15.3, R Core Team, 2013).

We used a two-way analysis of variance technique that allows the combination of multi-year samples to reduce age bias from gill net selectivity to assess for differences in year-class strength (Kimura, 1988; Maceina and Pereira, 2007). Catch-per-unit effort data from the 2000–2009 year-classes from collection years 2010–2012 were used in the analysis. Weaker year-classes were identified by negative least-squares means and stronger year-classes by positive least-squares means. The least-squares means were correlated with water depth data from the Goulais River to relate the year-class index to climate. Water depth data for Goulais River were available since 2002 from the Environment Canada Hydrometric database (Environment Canada, 2013). Year-class strength was also assessed against the timing of Sea Lamprey (*Petromyzon marinus*) control treatments, which occur on a cyclical basis in many of the tributaries to the Great Lakes. Treatments involve the application of a chemical lampricide to control larval lampreys, and there is concern that these treatments may negatively impact age-0 Lake Sturgeon (Boogaard et al., 2003).

Results

Abundance

In total, 531 unique Lake Sturgeon were captured in Goulais Bay between 2010 and 2012. Spatially higher catches occurred closer to where the Goulais River enters the bay, but sturgeon were captured across a broad area in the bay, with only two of the 72 net sets resulting in no Lake Sturgeon captures (Fig. 1). Twenty-eight Lake Sturgeon were recaptured during the course of the study; 15 fish were recaptured in the year that they were tagged, while the remaining 13 fish were recaptured either one or 2 years after their initial tagging. Mark-recapture analysis resulted in an estimate of 4,977 (95% CIs 3295–7517) juveniles in Goulais Bay.

The mean CPUE of Lake Sturgeon in Goulais Bay declined slightly over the 3 years of sampling, ranging from 8.0 to 6.5 sturgeon/net (Table 1). Despite this decline, catches in all 3 years were, on average, more than double that of any other Lake Superior tributary sampled with the same standardized sampling protocol (Table 1).

Table 1
Mean (±SE) catch of Lake Sturgeon in standardized gill nets from around Lake Superior. Goulais Bay data are from this study; data from remaining tributaries are from Schloesser et al. (2014)

Tributary	Mean catch (±SE)
Goulais – 2010	8.0 (2.0)
Goulais – 2011	7.0 (0.8)
Goulais – 2012	6.5 (1.0)
Bad	2.6 (0.6)
Batchawana	1.0 (0.3)
Black Sturgeon	2.4 (0.9)
Gravel	0.0 (0.0)
Kaministiquia	0.1 (0.1)
Michipicoten	0.5 (0.2)
Montreal	0.9 (0.4)
Nipigon	0.0 (0.0)
Ontonagon	3.5 (0.7)
Pic	3.6 (1.5)
Pigeon	0.0 (0.0)
Prairie	0.5 (0.2)
St. Louis	2.1 (0.8)
Sturgeon	0.5 (0.2)
Tahquamenon	0.1 (0.1)

Biological characteristics of Lake Sturgeon population

Captured Lake Sturgeon ranged in total length from 365 to 1510 mm, with a mean total length of 705 mm. The weights of captured sturgeon ranged from 200 g to 15 kg, with a mean weight of 2.3 kg. A wide variety of ages and year-classes were captured, although fewer older fish were seen in our sampling (Fig. 2b,c). Fish as young as age-1 and old as age-29 were observed, with a mean capture age of 7.7 years (Fig. 2b).

Lake Sturgeon growth was highly variable among individuals, and on average sampled fish grew slowly (40–50 mm year^{-1}; Fig. 2d). Despite the relatively young age of the sampled fish, we were able to fit a von Bertalanffy growth model successfully, which also indicated that growth was slow, with a Brody's growth coefficient of only 0.031 (Fig. 2d).

Mortality was estimated in two different ways. The daily survival estimate provided by the best fit MARK mark-recapture model was 0.9989884, which translates to a total annual survival rate of 0.691 (95% CIs 0.145–0.886). Catch-curve analysis indicated instantaneous total mortality to be 0.153 (95% CIs 0.085–0.221), while total annual survival was estimated higher at 0.858 (95% CIs 0.802–0.919; Fig. 3).

Recruitment patterns

Successful spawning was observed in almost every year from 1983 through 2010, as year-classes were regularly produced (Fig. 2c). Two-way analysis of variance indicated that there was limited support for some year-classes ($F_{9,8} = 3.2$,

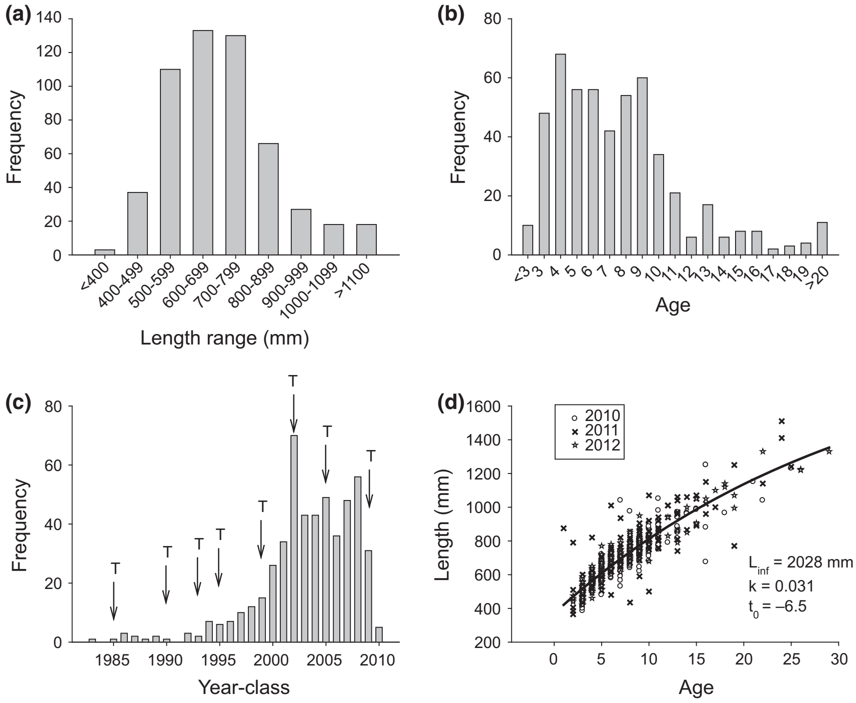

Fig. 2. Data for all four plots from Lake Sturgeon captured in Goulais Bay, all three (2010–2012) sampling years. (a) Frequency of total lengths (mm) by 100 mm length bins; (b) Age distribution; (c) Indication of year-class strength, based on age and year-of-capture. Years noted by T = year-class potentially subjected to a Sea Lamprey control treatment; (d) von Bertalanffy growth model for Lake Sturgeon captured with fish separated by year of capture. Line = all years combined fitted von Bertalanffy growth curve, with curve parameters, including asymptotic length (L_{inf}), growth coefficient (k), and initial fork length (t_0) located in lower right corner of the plot

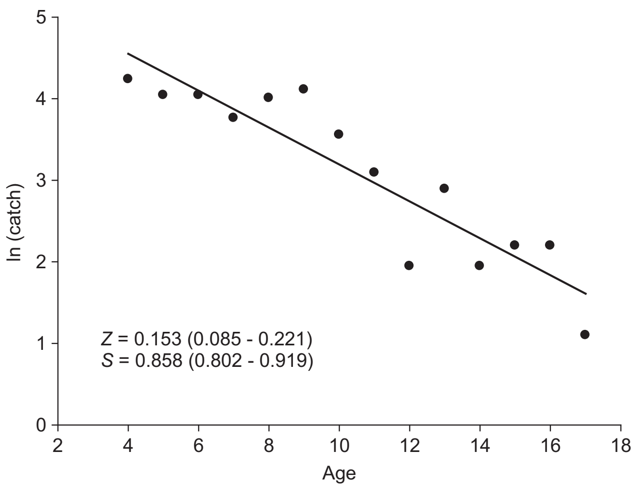

Fig. 3. Catch curve analysis, including rate of total annual survival (S) and instantaneous mortality (Z) for Lake Sturgeon captured in Goulais Bay, 2007 (assigned age-4) to 1994 (assigned age-17) year-classes. Numbers in brackets = 95% confidence intervals. Linear model: ln(count) = 4.528–0.153 Age assigned ($r^2 = 0.678$, $P < 0.001$)

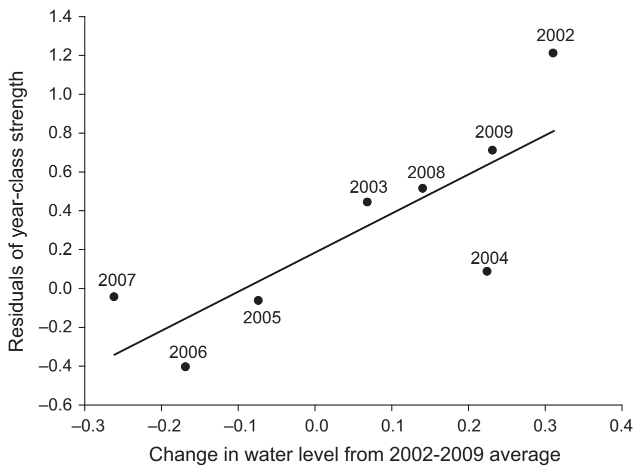

Fig. 4. Least-square mean year-class strength from Lake Sturgeon in Goulais Bay as a function of water depth (standardised to 2002–2009 mean), Goulais River, 2002–2009. Linear model: year-class strength = −0.039 + 0.81 May water depth index ($r^2 = 0.653$, $P = 0.015$)

$P = 0.056$) and ages ($F_{10,8} = 3.2$, $P = 0.053$) being more represented in our sampling. In particular, strong 2002, 2008 and 2009 year-classes are apparent (Figs 2c and 4). Year-class strength was positively correlated with May water depth ($r^2 = 0.65$) over the short hydrographic time series available to us (Fig. 4).

The Goulais River was treated for Sea Lampreys eight times from 1985 to 2009, with no evidence that control treatments eliminated Lake Sturgeon year-classes (Fig. 2c); they produced in similar numbers in treatment years and in non-treatment years and, in fact, the largest year-class coincided with a treatment year (2002).

Discussion

Lake Sturgeon populations in the Great Lakes basin are typically small and persist below levels recommended as restoration targets, with the exception of a few large populations in areas such as the Huron-Erie corridor and the Lake Winnebago system (Holey et al., 2000). In Lake Superior, it is unlikely that any of the remnant populations meet the abundance target set for a rehabilitated population of 1500 spawning individuals (Auer, 2003). Thus, the identification of a robust population of this species of conservation concern is a welcome discovery, even if most of the individuals captured are not yet of spawning age. In addition, the sampled population comprised broadly distributed year-classes, and assessed biological characteristics were comparable to other Lake Superior populations (Schloesser et al., 2014), a further indication of a population on the verge of recovery.

There is no estimate of the number of spawning Lake Sturgeon that ascend the Goulais River, the likely source of the primarily juvenile sturgeon captured in the bay. We do not know for certain the sturgeon in the bay originated from the river, as Lake Sturgeon in the south-eastern Lake Superior are genetically indistinguishable from each other and those populations along the north shore of Lake Huron (Welsh et al., 2008, 2010). That said, sturgeon are routinely tagged by management agencies around Lake Superior, and of the hundreds of fish we have handled the past few years in the south-eastern part of the lake only a single sturgeon was recaptured in a location where it was not originally tagged. This suggests there is limited movement among areas, and that it is likely that the majority of Lake Sturgeon in Goulais Bay originated there. Other, recent spawning population estimates from Lake Superior include the 844 spawners in the Bad River in 2010 (Schloesser and Quinlan, 2011), 350–400 spawners in the Sturgeon River in 2004 (Auer and Baker, 2007) and ~90 spawners in the Black Sturgeon River in both 2003 and 2004 (Friday, 2004). While the exact relationship between the abundance of juvenile Lake Sturgeon located near spawning tributaries and the number of spawning adults in those tributaries is unclear, research on other sturgeon species suggests that there is a positive relationship between adult and juvenile abundance (Colombo et al., 2007; Jarić et al., 2010). The consistently higher catches of juvenile Lake Sturgeon in Goulais Bay, in comparison to the rest of the spawning tributaries of Lake Superior, suggests that spawning abundance is also likely high (or at the very least will be high, when the sampled fish mature) in the nearby Goulais River.

Lake Sturgeon growth in Goulais Bay was faster for fish <20 years old than that predicted by Vélez-Espino and Koops (2009) for Lake Superior based on their growth models, although growth of older fish slowed and our oldest fish fit the predictions of their model. Lake Sturgeon growth is meaningfully impacted by latitude, with increasing latitude correlating with decreasing temperatures, which slows growth in more northern populations (Power and McKinley, 1997; Vélez-Espino and Koops, 2009). Goulais Bay is relatively shallow, and therefore likely warmer and more productive than most of the rearing habitat for Lake Sturgeon in Lake Superior, which might explain why growth was faster than predicted for younger fish. Growth in Goulais Bay was comparable to juvenile Lake Sturgeon sampled off other Lake Superior tributaries as part of the lake-wide juvenile sampling program (Schloesser et al., 2014), and other populations in the Great Lakes basin (Cuerrier, 1966; Fortin et al., 1993). In addition, our calculated growth coefficient of 0.031, while low, is comparable to that observed in other Lake Sturgeon studies (e.g. k = 0.019, Threader and Brousseau, 1986; k = 0.043, Noakes et al., 1999). We caution that because our assessment captured primarily juvenile sturgeon we had few older fish included in our von Bertalanffy analysis, which likely resulted in an underestimate of L_{inf} and an overestimate of growth (e.g. Fenton et al., 1991).

We found two different annual survival estimates with our two methods for assessing survival (catch-curve and mark-recapture). There is no agreement on the best way to estimate mortality in sturgeons (Phelps et al., 2013), and each method requires a number of assumptions (accurate aging, constant recruitment and mortality) (Hilborn and Walters, 1992). We know that aging older Lake Sturgeon typically results in an age underestimate (Bruch et al., 2009), but given our young ages we anticipate more accurate interpretations for juvenile fish. Our catch-curve estimate of 0.858 was similar to adult survival rates of 78–90% observed over 40 years in the highly successful Lake Winnebago system (Bruch, 1999). However, the assumptions for the catch-curve analysis are more restrictive than for the mark-recapture method (Hilborn and Walters, 1992; Miranda and Bettoli, 2007), and we recognize that size/age limitations from gillnet selectivity may reduce the use of this analysis. Furthermore, while we initially believed that our calculated estimates of survival using the mark-recapture method were low, and attributed this to the potential for significant migration out of Goulais Bay into other areas of Lake Superior, other sturgeon researchers have found comparable survival estimates (0.6998 for late stage juvenile Lake Sturgeon, Vélez-Espino and Koops, 2009; 0;.654 for similarly aged shovelnose sturgeon (*Scaphirhynchus platorynchus*; Phelps et al., 2013). The mark-recapture analysis has fewer assumptions, but is influenced by potential tag loss (although likely not an issue in this study as we triple-tagged our study animals). Additional years of data collection, resulting in more recaptures, will continue to increase our confidence in this mark-recapture estimate.

Our study found little evidence of boom-bust recruitment cycles in Lake Sturgeon, as year-classes were produced nearly every year. There were some years with relatively higher recruitment, but never more than a 4-fold variation in recruitment over the past 10 or so years. A similar pattern was observed in other Lake Superior tributaries sampled as part of the lake-wide juvenile sampling program (Schloesser et al., 2014). This appears to be unusual, as variable recruitment has been observed in a number of Lake Sturgeon populations [e.g. Lake Winnebago (Priegel and Wirth, 1975); St. Lawrence River (Nilo et al., 1997); Groundhog and Mattagami rivers (Noakes et al., 1999); and Rainy Lake (Adams et al., 2006)]. In particular, Nilo et al. (1997) found a 7-fold difference in recruitment attributable to higher spring flows and water temperatures. Similarly, positive correlations were observed between spring flows and year-class strength of juvenile white sturgeon *Acipenser transmontanus* (Kohlhorst et al., 1991) and shovelnose and pallid sturgeon *S. albus* (Phelps et al., 2010). Increasing water depth in May, the likely spawning period for Lake Sturgeon in the Goulais River, was likewise correlated with year-class strength in our study despite the limited differences in year-class strength. This would suggest that spring flows help produce stronger year-classes in this system, although in general the population appears to be robust to climatic variation and capable of reproducing successfully in most (if not all) years.

The effect of lampricides on non-target fishes has been a concern since the development of a lampricide application program to control invasive Sea Lampreys in the Great Lakes since the 1960s (Applegate and King, 1962). Specific concerns about lampricide impacts on Lake Sturgeon have arisen more recently (Boogaard et al., 2003), but there is scant data on which to assess whether lampricide treatments negatively affect age-0 Lake Sturgeon survival. Our results clearly indicate that no large-scale Lake Sturgeon mortality events have occurred in conjunction with Sea Lamprey treatments in the Goulais River, as there are no missing or reduced year-classes in conjunction with Sea Lamprey treatment years. This does not mean that there are no impacts, as age-0 Lake Sturgeon may already have migrated out of the river prior to lampricide treatments (for example), but in this case any potential impacts are not being realized at the population level.

In summary, we report here on the identification of a large population of juvenile Lake Sturgeon in Goulais Bay, Lake Superior. This population could possibly be the largest in the Lake Superior basin, based on the results of similar surveys of juveniles on all other tributaries to the lake. The success of this population is likely due to the length of river (>50 km) available for spawning before reaching a barrier on the Goulais River, and the relative productivity of Goulais Bay for feeding juvenile, sub-adult and adult sturgeon. Suitable habitat is relatively rare in Lake Superior, as the inshore zone (<15 m depths) makes up only 7% of the lake surface area (Gorman et al., 2010). It is possible that in the future this robust Goulais Bay Lake Sturgeon population could help re-populate the south-eastern part of the lake, which contains a suitable number of large embayment areas. This assumes that there is movement between embayment habitats, which has occurred in the past based on the lack of genetic differentiation between Lake Sturgeon populations in this part of the lake (Welsh et al., 2010). To support our contentions, we recommend that additional work be undertaken to assess (i) the size of the spawning run in the Goulais River to confirm the potential importance of this population, and (ii) potential movement between suitable habitats (Whitefish Bay, Goulais Bay, Batchawana Bay) in the south-eastern part of Lake Superior.

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